Chapter 1
Introduction

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The Deep Space Network (DSN) is a National Aeronautics and Space Administration (NASA) facility. It is managed, technically directed, and operated by the Jet Propulsion Laboratory (JPL) of the California Institute of Technology (Caltech). The objectives of the DSN are to maintain communications with spacecraft. This consists of collecting telemetry data from the spacecraft, transmitting command data to them, providing spacecraft trajectory data to mission operations and scientists, and monitoring and controlling the network performance. Other objectives are to gather science data from spacecraft, to measure variations in transmitted radio waves from spacecraft for radio science experiments, and to perform very-long-baseline interferometry observations. The DSN is the largest and most sensitive scientific telecommunications and radio navigation network in the world.

The DSN consists of three deep-space communications complexes (DSCC) separated by approximately 120 degrees (deg) of longitude around the world:

1) Goldstone, California
2) Near Madrid, Spain, and
3) Near Canberra, Australia

This placement allows continuous 24-hour observation of spacecraft as the Earth rotates, and it provides sufficient overlap for transferring the spacecraft radio link from one complex to the other.

The precursor of the DSN was established in January 1958 when JPL, under contract to the U.S. Army, deployed radio tracking stations in Nigeria, Singapore, and California to track the first successful U.S. satellite, Explorer 1. Army funding for JPL continued until the National Aeronautics and Space

Administration was officially established in October 1958. Two months later the Army contract with Caltech, which provided funding for JPL, was transferred to a NASA contract, and JPL's primary funding continues through NASA to this day. The Laboratory's employees always have been, and remain to the present, employees of Caltech [1].

At about this time in 1958 the concept of a separate Earth-based communications network was established. Shortly afterward, NASA created the Deep Space Instrumental Facility (DSIF) as a separate Earth-based communications facility that would support many space flight missions simultaneously, thereby avoiding the impractical duplication of a specialized space communications network for each flight project. A separate facility, located on the JPL campus, was the Space Flight Operations Facility (SFOF), which communicated with all the DSIF stations through a Ground Communications Facility (GCF), also a separate organization from the DSIF. The network was given responsibility for its own research, development, and operation, in support of all its users. In 1963 the DSIF was combined with the multi-mission part of the SFOF and the GCF to form the DSN. Under this concept it became a world leader in the development of large antennas, low-noise receivers, tracking, telemetry and command systems, digital signal processing, and deep-space radio navigation. These functions are incorporated in a state-of-the-art telecommunications system that can be upgraded to meet the requirements of new missions while maintaining support for current missions. This book concentrates on the low-noise front-end of all the DSN receivers and the calibration of the large antennas, whereas other technologies are covered by other books in this Deep Space Communications and Navigation series.

Each of the three DSCCs around the world has one 70-meter (m) antenna, one 26-m antenna, and several 34-m antennas.

A single antenna with its associated equipment is called a Deep Space Station (DSS) and the entire location is called a Deep Space Communications Complex (DSCC). All the stations are remotely operated from a centralized Signal Processing Center (SPC) at each DSCC. Once data has been processed at a DSCC, it is transmitted to the SFOF for further processing and distribution to the various science teams over conventional ground communications networks.

Figure 1-1 is a photograph of the 70-m antenna at Goldstone. In addition to spacecraft tracking, this antenna is used for radio and radar science. The 70-m antennas in Spain and Australia are essentially identical, and they are used for spacecraft tracking and some radio science. The 70-m antennas each have three Cassegrain feedcones in the center of the antenna, which contain the receive and transmit equipment portion of the station. Figures 2-1, 2-2, and 2-3 show the three feedcones, termed a "tricone", on the reflector surface. A slightly

Fig. 1-1. 70-m antenna at Goldstone DSCC.

asymmetric Cassegrain subreflector is used, which can be rotated about the symmetric focal axis of the main reflector. Rotation provides a large outdoor, mechanical, ultralow-noise microwave "optical" or freespace bandswitch for "connection" to any one of the three feedcones. Each feedcone is placed on the Cassegrain focus-circle as formed below the subreflector. Perfect main reflector boresight pointing results for any one of the three feeds used, the asymmetric subreflector and tricone design causes almost no final or exit beam "scan" loss. In practice only two of the three feedcones are brought into focus for operations. The third is used for engineering purposes and science observations. The S-band feedcone is always directed to the X-band feedcone's dichroic plate and reflected toward the subreflector.

Nearly uniform feed illumination of the main reflector is achieved by the use of shaped dual reflector principles in the asymmetric environment. The combination of switchable tricone microwave feed systems with shaped high-gain efficiency techniques, results in highly flexible large antennas capable of high-performance operation in several internationally-allocated deep space microwave frequency bands with high performance.

X-band receive only, or X-band receive and transmit, operations are conducted with a high pass dichroic frequency-selective reflector placed on top of the X-band (XTR) feedcone, in the retracted position (Fig. 2-2). The XTR feedcone system can transmit with the dichroic plate either extended or retracted. Simultaneous S-band and X-band operations, with or without S-band transmit, are conducted with the dichroic plate in the extended position (Fig. 2-3). X-band passes through the extended dichroic plate while S-band is reflected towards an ellipsoidal reflector on top of the S-band polarization diversity (SPD) feedcone. Thus, by means of two relatively small (sub-sub) reflectors, simultaneous use of two of the three tricone feedcones is obtained, with near-perfect pointing (co-axial S- and X-beam), and essentially no beam scan loss.

The DSN consists of three 70-m antennas, three 34-m High Efficiency (HEF) antennas, six Beam Waveguide (BWG) antennas, one 34-m High Speed Beam Waveguide (HSB), and three 26-m antennas, distributed among the three complexes.

The microwave feed systems of the BWG antennas are placed indoors in a subterranean room, mostly protected from local weather effects, which results in improved link performance during rain. When combined with the uniform illumination shaping technique similar to that of the 70-m antennas, the DSN 34-m BWG antennas are similarly capable of operation with high performance and flexibility of operational frequencies, (Fig. 7-3). A four-reflector, very low-loss 3-m diameter "mirror relay" system in a shielded tube, is used to transfer signals to and from the Cassegrain focus of the main reflector and the secondary focus in the subterranean room. The room contains additional ellipsoidal flat and dichroic reflectors to combine several frequency-band feed systems, which include the low-noise preamplifiers, the high power transmitter, and the control and calibration equipment.

In the HEF antennas, a constant-beamwidth, common aperture S- and X-band (S-/X-band) feedhorn is used at the Cassegrain focus, in a conventional outdoor single-feedcone arrangement. These antennas are called High

Efficiency antennas because they were the first DSN antennas to use the uniform aperture illumination technique.

The DSN 26-m antennas are planned for decommissioning in 2008. They are currently used for tracking near-Earth missions, and this function will be transferred to the 34-m antennas after the decommissioning.

One of the 34-m antennas at the Goldstone DSCC was decommissioned in 1996 and is no longer considered a DSN tracking asset. However, it remains a NASA/DSN asset. The Goldstone Apple Valley Radio Telescope (GAVRT) program was set up as a JPL outreach venture between the Lewis Center for Educational Research (LCER) and JPL, to bring hands-on science to America's classrooms. GAVRT uses the decommissioned, but DSN maintained, antenna at the Goldstone site to conduct radio astronomy observations of scientifically significant objects by remote control, to give the students a real-world experience of scientific discovery, (see, for example, Section 7.6.2 in Chapter 7). By the end of the year 2006, 176 schools in 27 U.S. states, 3 U.S. territories, and 13 foreign countries with U.S. schools, have been involved with the GAVRT program. Much of the equipment and many of the measurement techniques described in this book are applied to the GAVRT observations and system calibrations.

The communication between the ground network and a spacecraft at planetary distances presents special problems, both unique and challenging. Communications performance scales as $1/R^2$, and the extreme distances involved in the exploration of the Solar System make ultralow-noise preamplifiers necessary. To put this in perspective, consider first a typical geostationary communications satellite at an altitude of 40,000 km (4×10^4) above the Earth's surface. The outer planets are many times farther from the Earth, for example the range to Neptune is about 4.5×10^9 km. The distance difference between these two examples varies by more than a factor of 100,000, which implies that the communications challenge for the space research spacecraft is ten orders of magnitude larger than that of the geostationary link.

This book describes the low-noise microwave systems that form the front end of all the DSN ground stations. The microwave front end of each antenna is key to establishing the sensitivity, polarization, frequency diversity, and capabilities of the receiving chain, and therefore of the entire ground station. The receiving system sensitivity and capability is defined by G/T, where G is the antenna gain and T is the overall noise temperature of the entire receiving chain, usually called system operating noise temperature, T_{op}. To improve the station's receiving performance, it is necessary to improve G/T, which can be done by increasing antenna gain, by decreasing T_{op}, or both. In the past the DSN has both increased G and reduced T_{op}. It has been somewhat easier, and therefore more efficient and cost effective, to decrease T_{op} than it has been to increase the antenna gain.

As the microwave front end of the station is crucial to establishing the sensitivity and capability of the receiving chain, it is therefore incumbent on the designers of the receiving system to expend considerable effort in reducing T_{op} and in calibrating and maintaining the low-noise front end. The more accurately T_{op} can be defined, the narrower the tolerances on the design of a spacecraft mission that can be accepted. The reduction in a project's design tolerances on spacecraft power is worth a considerable amount of money, and enables more science data for the same spacecraft power, and hence the importance of the calibration of the receiving chain. Accurate calibrations are also necessary for the maintenance of the low-noise performance of each antenna system. All missions and radio science benefit from the high gain and extreme sensitivity of the performance of the DSN.

The cost of receiving data from distant spacecraft in dollars per bit is proportional to the receiving system's noise temperature. Each time the system noise temperature is reduced by half, the maximum transferable data rate is doubled, and the cost per bit is reduced by half. Over the years the DSN has developed remarkable innovations to reduce system noise temperature, and many examples have been documented. A 20-percent, or 3-kelvin (K), reduction in the S-band T_{op} enabled the reception of 117 thousand bits per second (kbps) from Mariner 10 during the Mercury flyby in 1974 [2]. This resulted in continuous image coverage of Mercury along the spacecraft's flight path. Without the T_{op} reduction, the mission would have been forced to use a 22-kbps data rate, and 80 percent of the data would have been lost. Support of the Galileo mission is a similar example. Furthermore, an X-band T_{op} reduction of about 20 percent in 1980 contributed to higher data rates from the Voyager spacecraft at Saturn, Uranus, and Neptune. The implementation of the X-/X-/Ka-band feed system in the BWG subnet reduced the X-band diplexed (transmit and receive) T_{op} from 36 K to 18 K for a 3-decibel (dB) improvement in system noise performance [3]. The same technology improved the 70-m X-band T_{op} from 39 K to 15 K for the Cassini mission to realize per day data downlink at Saturn [3].

Mission planners have the option of increasing the data rate from a deep-space mission and thereby reducing the tracking time needed to return the same volume of data, or increasing the total volume of data received. The percentage reduction in tracking time can be the same percentage by which the T_{op} is reduced. A reduction in the tracking time results in reduced costs to a mission for tracking support. Use of the time saved with an increase in the data return enables a greater percentage of data to be returned than the percentage reduction in tracking time; a 20-percent reduction in T_{op} enables a 25-percent increase in data rate. The value of a T_{op} reduction can be based on the costs of using DSN antennas to track deep-space missions. Hourly rates for the use of DSN antennas have been estimated for mission planning purposes. These rates, combined for the DSN's various antennas were used to show that a 20-percent reduction in T_{op}, 4 K at X-band, could save a few tens of millions of dollars per year [4]. A reduction in T_{op} also means a higher antenna utilization time.

Another way to estimate the value of a T_{op} reduction considers the initial cost and the operations cost of a fully equipped 34-m BWG antenna over, say, a 20-year period. The construction and implementation cost of approximately $33M combined with a $2M per year operations cost over the 20-year lifetime gives a total lifetime cost of about $73M. Adding five such 34-m antennas to the DSN increases the total data reception capability by about 25 percent. Reducing the X-band system noise temperature by 4 K, or 20 percent, increases the DSN's total data reception capability by about 25 percent. By this measure, a 1-K reduction at X-band throughout the DSN is worth about $91M, and, in this case, a 20-percent reduction in T_{op} appears to be worth about $365M [4].

The conclusion is clear; noise in the DSN is extremely expensive. The DSN has devoted considerable time and effort to reducing T_{op} and to the concomitant activity of accurately calibrating T_{op}. Interesting and innovative concepts and methods have been developed in both these projects. This book describes and discusses these developments.

Chapter 2 begins with a standard, but brief, review of noise in receiving systems in general, and goes on to describe all the noise element contributions, both internal and external, that make up the total noise in the system operating noise temperature. All noise contributions are detailed in their measurement and calibration, with emphasis on the achievement of maximum accuracy and precision. Each step in the process is analyzed with mathematical rigor, so that the reader who wishes to follow the logic trail throughout the system can do so compactly. On the other hand, the method of measurements and calibrations is described fully, including gain fluctuations and system linearity. This gives an overall view of what needs to be done, how it is done, and why it is important. Step-by-step details allow an operator to carry out the measurements and calibrations and derive the results of the statistical error analyses with little, or even no consideration of the mathematics or theory. Many carefully selected references are provided for those readers who want more detail or who like to read around each topic.

The ruby maser microwave preamplifiers in the DSN are linear, phase-preserving, and ultralow-noise. They are the most sensitive and lowest noise amplifiers used in the field. Yet over many years in the DSN they have proved to be rugged and stable, as well as providing a natural spectrum filtering capability few other amplifiers can match in low-noise systems. Chapter 3 introduces ruby masers in general and the relevant properties of ruby. The mechanism of microwave amplification by stimulated emission of radiation (maser) is described with some theory to give an overview of the entire amplification process. The remarkable low-noise properties of masers is shown to be derived primarily from the amplification process, but also from the innovative engineering developed by the DSN to integrate the masers into the front-end subsystem. Cavity masers, reflected wave masers, and comb-type masers are included. Detailed mathematical theory of the maser process is provided for completeness, including the noise temperature performance and gain dependence of masers, together with references for further study if needed.

Chapter 4 completes the maser discussion with a description and analysis of the JPL-developed closed-cycle refrigerator (CCR), and other refrigeration systems used to support the masers. The chapter describes radiation shields, heat leaks, and other engineering details needed for the analysis and operation of CCRs in the field.

Chapter 5 is a comprehensive discussion of high electron mobility transistors (HEMT), and it includes theory, practical operation, calibrations, device fabrication and optimization, noise modeling and characterization, amplifier development, and subsystem measurements. The chapter gives a complete overview of the entire subject of HEMT amplifiers with mathematical derivations, details of materials and fabrication, amplifier design and operation, and measurements and calibrations. The chapter can be used both as a HEMT textbook for detailed study, as well as an introduction to the use of HEMTs for operators and managers who only need an overview of their fabrication and use in the field.

The atmosphere has a significant effect on the communications link between the ground and the spacecraft, especially at the higher operating frequencies. The atmosphere attenuates the signal and adds noise temperature to the ground receiving system, and changing weather conditions change these parameters. Sometimes large fluctuations of the parameters are experienced. Chapter 6 is a description and discussion of how the DSN handles the problem of changing weather conditions. The DSN uses direct weather measurements by water vapor radiometers (WVR), along with meteorological forecasts and a JPL-derived standard surface weather model. The WVRs are described, and the theory of the derivation of the required parameters is presented. The development of the JPL standard weather model is described, including how it is used together with meteorological forecasts.

This book is focused on the system operating noise temperature, and the need for and the importance of, the measurement and calibration thereof. However, as stated above, the system sensitivity and quality are defined by G/T, where G is the antenna gain and T is the total system noise temperature. The book would not be complete without a discussion of the measurement and calibration of antenna gain and efficiency. Chapter 7 is an overview of this extensive subject, which will be treated in more detail in a future book in this series. This chapter uses the principles of noise temperature measurements, as described in Chapter 2, to derive antenna gain, systematic pointing corrections, subreflector focus, and calibration of radio sources used in the antenna gain assessment.

With new technology developed at JPL, it has been possible to obtain measurement precision yielding as much as an order of magnitude improvement over previous methods in the determination of antenna aperture efficiency, and factors of five or more in the determination of pointing errors and antenna beamwidth. This raster-scan improvement has been achieved by performing continuous, rapid, raster scans of both extended and point sources. This mapping technique for antenna and radio source calibration is called "on-the-fly" mapping. The chapter begins with a description of the general requirements for DSN antenna calibrations, followed by a discussion of current methods and their shortcomings. The final section describes the new mapping technique with some results. Two of the most important parameters that determine antenna gain are the alignments of the main reflector panels and antenna stability. These are best measured by coherent holographic techniques, which are described in the final chapter, Chapter 8.

When applied to reflector antennas, microwave holography is a technique that uses the Fourier transform between the complex far-field radiation pattern of an antenna and the complex aperture distribution. The result of this operation is a data set of aperture phase and amplitude distributions. These data are used to precisely characterize crucial performance parameters, which include panel alignment, subreflector position, antenna aperture illumination, directivity at various frequencies, and the effects of gravity deformation. Thus, the holography technique provides a method for analysis, evaluation, and RF performance improvement of large reflector and beam waveguide antennas. Microwave holography is one of the most economical techniques for increasing the performance of the large DSN antennas in terms of cost-to-performance ratio. Chapter 8 describes the design and use of the holographic measurement system and its use in the DSN to improve, optimize, and maintain its performance to prescribed specifications. The chapter describes the design of the holographic instruments, and the mathematical algorithm and software for the development of the holographic measurement system. Microwave holography is one of the important items in the DSN suite of calibration instruments and methodologies.

To the extent possible, this book adheres to Institute of Electrical and Electronics Engineers (IEEE) standard terminology definitions [5]. This is an important consideration for clarity, understanding, and cross-referencing throughout the text. An example of the difficulty that arises when authors do not use standard terminology is given in Mumford and Scheibe's book, Noise; Performance Factors in Communications Systems [6], where they list nine different definitions of amplifier noise factor in terms of noise temperature used by various authors. This clearly shows the importance of using IEEE noise standards [5,7] for the definition of receiving system noise terms.

Each chapter in this book can be read in three levels. Rigorous mathematical theory of the devices, their operation, and calibration methods, is one level. An overview of the design, and in some cases the fabrication of the devices, how they are constructed and used in the field, their measurements and calibrations, form a second level. This level will be useful for engineers and supervisors. In addition, the book can be read on a third level of advice, instructions, and methods. The information presented at this third level was derived from much experience in the field, and this level will be useful for technicians and operators.

References

[1] C. R. Koppes, *JPL and the American Space Program*, Yale University Press, New Haven, Connecticutt and London, United Kingdom, 1982.

[2] W. R. Corliss, *The History of the Deep Space Network*, NASA, CR 151915, National Aeronautics and Space Administration, Washington, District of Columbia, 1976.

[3] J. Bautista, R. Clauss, S. Petty, and J. Shell, "DSN Low Noise Amplifiers in the New Millennium," *TMOD Technology and Science Program News*, Issue 13, Rev. 1, Jet Propulsion Laboratory, Pasadena, California, January 2001. http://tmot.jpl.nasa.gov/index.html

[4] J. Layland and L. Rauch, "The Evolution of Technology in the Deep Space Network: A History of the Advanced Systems Program," *The Telecommunications and Data Progress Report 42-130, April–June 1997*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–44, August 15, 1997, (also available as JPL publication 95-20 at http://tmot.jpl.nasa.gov/, click on Program Overview Information). http://ipnpr.jpl.nasa.gov/progress_report/

[5] *The Authoritative Dictionary of IEEE Standard Terms*, 7th ed., *IEEE Standards 100*, Hoboken, New Jersey, 2000.

[6] W. W. Mumford and E. H. Scheibe, *Noise; Performance Factors in Communications Systems*, Horizon House–Microwave Inc., Dedham, Massachusetts, 1968.

[7] "IRE Standards on Electron Tubes: Definition of Terms, 1962 (62 IRE 7.S2)," *Proceedings of the IEEE,* vol. 51, pp. 434–435, March 1963.